SECTION II.—GENERAL METEOROLOGY.

INFLUENCE OF TERRESTRIAL ROTATION ON THE CONDITION OF THE ATMOSPHERE AND OCEAN.

By J. W. SANDSTRÖM.

[Dated, Statens Meteorologiska Centralanstalt, Stockholm, July 30, 1914.]

1.

The more one seeks to comprehend the atmospheric and oceanic phenomena, so much the more does terrestrial rotation come prominently to the front as one of their most important causes. Indeed, its effects appear in a very puzzling and peculiar manner, since numerous phenomena are quite inverted by reason of the terrestrial rotation. If the earth were at rest the atmospheric pressure at sea level would increase with increase of latitude, whereas on our rotating earth almost the opposite is the case. On a stationary earth warm light air would ascend to higher levels and cold, heavy air would sink downward, whereas on the rotating planet the opposite procedure is more frequent since, as a rule, the ascending air of cyclones is cold and specifically heavy, while the descending air of anticyclones is warm and specifically light.

It is no easy matter to clearly understand the actual method of action of the earth's rotation. I think this is due primarily to the fact that man is not provided with any sense that enables him to appreciate this rotation. From childhood on we are accustomed to regard the visible portion of the earth's surface as at rest. To be sure, we all know that the earth does really rotate and we can imagine this, but we have no sense by which to feel it. At times, perhaps, some industrious astronomical observer has had an occasional illusion of a rotating earth; but this true reality must have impressed him as an unreal deception. On the other hand, the constant deception that the earth is at rest, although it is really rotating, impresses the observer as being the true state of affairs.

Under these conditions it is indeed very natural that even the effects of the earth's rotation should appear foreign to us. In order to deduce them one must employ Coriolis's Theorem.[1] Undoubtedly this is adequate to compute all the consequences of terrestrial rotation, but its application[2] is not simple and this, I believe, is because the results impress us as strangely as does the fact of terrestrial rotation itself. For example, Coriolis's Theorem enables one to understand why, in the cyclone, specifically heavy air has a tendency to ascend and to compute the force that drives it upward. But the computation is distasteful to us, and we draw the inference that the calculation is erroneous because the results appear so contrary to what we expected. On the other hand, a being who can feel the terrestrial rotation would probably find it very natural that specifically heavy air has a tendency to ascend and specifically light air to descend. That person would find it easy to apply Coriolis's Theorem, because the resulting conclusions would be in harmony with his sensations.

This lack in the human senses seems to me to be one of the most serious obstacles to the introduction of dynamic methods in practical meteorology and hydrography. It is a simple matter to record the actual conditions and their changes, as well as to work up the observational material already collected from different points of view. But as soon as one attempts a near approach to the inner relationships of the phenomena enormous difficulties spring up. Thus, we have good grounds for assuming that the distribution of atmospheric pressure is intimately related to that of temperature and heat. It is also generally conceded that if this fundamental relationship could be formulated, purely practical meteorology would be greatly benefited. At first glance, also, the task seems to be very simple; if the air is warmed anywhere there it becomes specifically light and no longer presses so heavily upon the underlying surface. In consequence the air pressure decreases, i. e., a barometric depression is formed. This simple and clear consideration holds true for the conditions of the equatorial region between the horse latitudes where terrestrial rotation has little influence, but it does not at all apply in the higher latitudes. In these latter regions the lowest atmospheric pressure generally occurs precisely where the air is cold and specifically heavy (that is in the cyclones) and consequently ought to be pressing most heavily upon the underlying surface. This paradox is all the more exasperating because it seems to be quite uncalled for. Consequently we content ourselves with reporting the problematical phenomenon which contradicts all logic, and are not willing to suggest an explanation.

2.

I think that the detailed reasons above given make it of special importance to utilize any possible means that can help to visualize the effect of terrestrial rotation upon gases and liquids. Thus far I have found the best means to be hydrodynamic experiments with rotating vessels. These experiments present in an astonishingly simple manner some of the most important paradoxical phenomena of air and sea, and one can readily ascertain their causes because we are able to sense the rotation. For this reason such experiments should be employed to demonstrate to university classes the influence of the earth's rotation upon atmospheric and oceanic processes.

While performing and discussing these experiments one is soon led to a line of thought different from that of Coriolis, much more limited to be sure, but one that in many cases explains the processes in a simpler and less constrained manner. Indeed, one may consider these experiments from two different standpoints, both of which are useful. On the one side we may imagine that a very small intelligent individual is on the rotating vessel, a being of such small size and of such limited observational power that he can not recognize the rotation of the vessel. To such a small individual many of the processes in the vessel would appear extraordinarily

[1] Gustav Gasper Coriolis (1792–1843, Sept. 19, Paris) was an eminent French physicist; he was elected a member of the Académie des Sciences (Paris) in 1836. His Theorem was the kinematical proposition that the acceleration of a point relative to a rigid system is the resultant of the absolute acceleration, the acceleration of attraction, and the acceleration of compound centrifugal force. This proposition was probably first published in 1829 in his work "Traité de Mécanique," Paris, 1829, and in its second edition of 1844.

Director Nils Ekholm presents an exposition of Coriolis's Theorem in this REVIEW for June, 1914, 42 :331–333.—[C. A.]

[2] See Nils Ekholm in MONTHLY WEATHER REVIEW, June, 1914, 42 :333, ffg.

problematical. For example, by experiments carried out on a small scale he would find that liquids and gases specifically lighter than their surroundings will strive upward; but would find just the opposite rule when he regards the conditions in the vessel on a large scale. At first he would think his observations were incorrect or affected by local influences; gradually, however, the observations would be confirmed. Eventually numerous observations would lead him by indirect ways to the conclusion that the vessel probably has a rotating motion and then mathematical reasoning would enable him to determine how this new fact had influenced the conditions. Thus he would have deduced Coriolis's Theorem, and finally by applying that theorem he would succeed in satisfactorily explaining several of the observed peculiarities.

The second standpoint regards the rotating vessel from without and observes the phenomena taking place there. In this case it would appear as a result of the rotation of the vessel, that rotary movements predominate therein, movements to which one can directly apply the simple and comprehensible laws and experiments relating to centrifugal force. Much that appeared problematical under the former point of view now appears quite natural.

On applying to the earth the first method of consideration, that of experimentation, the small, intelligent individual of defective senses is represented by man himself. The second method of consideration presents matters as they would appear to an observer outside of the earth studying the processes of the atmosphere and the oceans from such a position. He would see a series of grand vorticular motions to which he would apply the principles of the law of centrifugal force. The advantage of this method of consideration consists in the fact that one may thereby see and judge of the whole absolute motion and the associated forces without any intermediary. In the former method one is concerned with two motions: The relative motions of the atmosphere or of the ocean water, as referred to the earth's surface, and the motions of the earth's surface as the result of its rotation. The compounding of these two motions and of the forces that bring them into existence is not always a specially easy problem. Nevertheless, so long as man possesses no external sense by which he can feel the earth's rotation, Coriolis's Theorem will be indispensable for him, and the hydrodynamic experiments with rotating vessels will be an excellent means of becoming practically acquainted with this law. The experiments should be considered first from the second or absolute point of view and then immediately transferred to the first or relative standpoint. By this comparison of the two methods one will gradually acquire the ability to intuitively take immediate account of the effect of terrestrial rotation when discussing the relative movements that we observe on the earth. I designate this acquirement as one of the most important objects of the present dynamic meteorology.

3.

In order to demonstrate this comparative method of discussion I need describe only a single experiment. Suppose it be desired to present experimentally the heaping up of the warm ocean water in the horse latitudes—there is provided a vessel of the dimensions 30×10×10 centimeters, having its longitudinal walls of glass. This vessel is filled to a depth of about 3 centimeters with fresh water, and then an equally deep layer of salt water is [gently] introduced beneath the fresh water. One of the water strata is colored with ink so that the form of its surface can be readily observed. Now, with the aid of a pair of bellows, a tube and the perforated spout of a watering pot, we direct a current of air down upon the water surface as indicated in figure 1.

At once it becomes clear that the bounding surface between the two strata of water bulges upward beneath

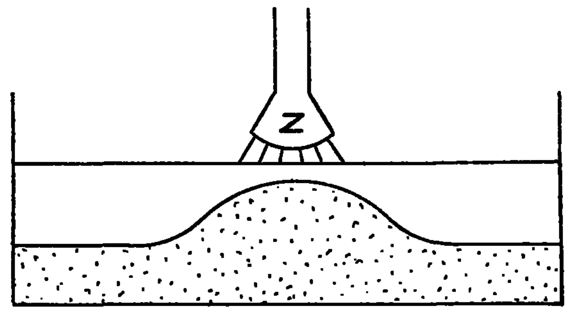

FIG. 1.—Effect of radially directed winds upon a system at rest.

the downward current of air; this is a natural result of the air blowing down upon the surface water and driving it toward the two ends of the vessel. We now place the vessel of water upon a rotatory table and set the table with the vessel in slow rotation about a vertical axis by means of a rotator. On blowing down upon the water surface as before, we find that the bounding surface of the two

FIG. 2.—Effect of radially directed winds upon a rotating system.

layers does not bulge upward at a point beneath the spout but, on the contrary, is depressed as shown in figure 2. This heaping up of the surface stratum beneath the air current is obviously associated intimately with the rotation of the vessel. From the experiment one readily concludes that the heaping of ocean water under the horse latitudes is the direct result of the earth's rotation in combination

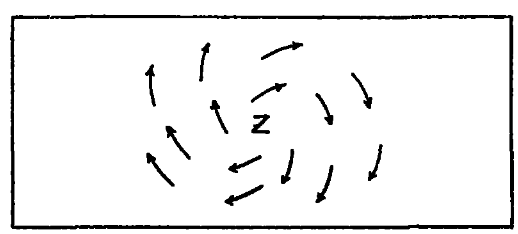

FIG. 3.—Relative motion of radially directed winds at the surface of a rotating system. (Viewed from above.)

with the anticyclonic atmospheric conditions prevailing there.

We may now endeavor to explain this phenomenon from the point of view of the small imaginary being that was cited in Section 2. This being observes the air movement relative to the rotating vessel and perceives that the air blows spirally outward from a center. (See fig. 3.)

This air movement produces also an anticyclonal circulation in the water, whereby on account of the deflective force this rotation comes into action and drives the water toward the right hand; in other words, it presses toward the center and the water heaps up at the center.

From the second point of view we see at once that the vessel is in rotation and then that there is air blowing radially from a central point upon the water surface. (See fig. 4.) The lower stratum has the same velocity of rotation as the vessel itself, but the rotation of the surface water is hindered by the radial air currents, so that this surface water moves somewhat more slowly than does the vessel. Accordingly the centrifugal force of the lower water stratum exceeds that of the upper. Hence the lower water is forced outward while the upper stratum collects in the center.

4.

This example presents the difference between the two methods of consideration. When it is desired to apply the second or absolute method of consideration to hydrologic and meteorologic processes, one must first of all recall that, in consequence of the earth's turning about its axis, its surface is everywhere in cyclonic rotation and that its velocity of rotation is determinable by the Foucault Pendulum experiment. If the earth's angular velocity of rotation is w, then the angular velocity of any point on the earth's surface is $w\sin\phi$, where ϕ is the geographic latitude of the place in question, and the time required by the earth to complete one rotation amounts to $24/\sin\phi$ hours. These reflections show that air that is apparently at rest actually possesses a considerable cyclonic circulation; in fact even the air caught in the familiar anticyclonic whirl actually possesses a cyclonic rotation. Accordingly it is clear that air apparently at rest is exposed to a considerable centrifugal force which is reinforced under cyclonic conditions and weakened under anticyclonic circulation. These facts explain completely the temperature distributions found within cyclones and anticyclones. In a cyclone *the cyclonic rotation at first increases with altitude* until at a certain height it attains its maximum, above which height the rotation suffers a diminution upward. The centrifugal force of the air is greatest at that level where the cyclonic rotation is strongest; hence at this level the air is driven most strongly outward, while below this level consequently the air is drawn upward and above this level it is drawn downward. Therefore, the air undergoes dynamic cooling below the level of maximum cyclonic rotation and dynamic warming above that level. This is the origin of the temperature distribution that has been found in cylcones. In an anticyclone the anticyclonic rotation has its maximum at a certain level where the centrifugal force is smallest, and from that level the centrifugal force increases both upward and downward. Consequently, below this level the air will be drawn downward and above it will be drawn upward; therefore, below this level the air will be warmed dynamically and above it will be cooled—deductions that agree with the observed temperature-distribution within anticyclones.

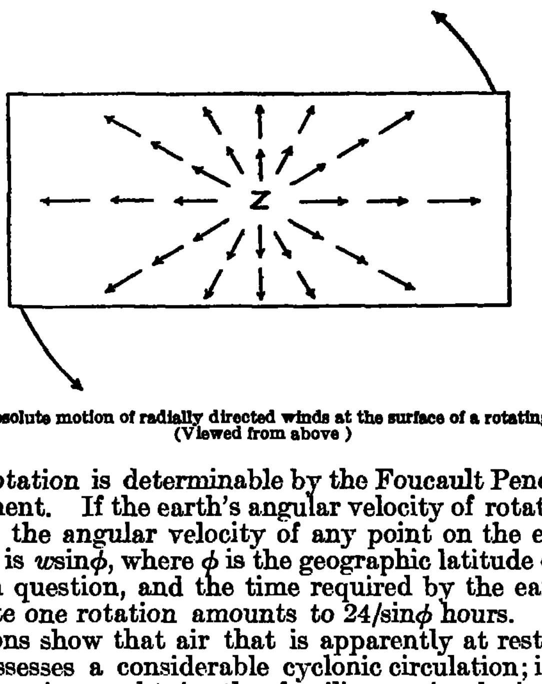

FIG. 4.—Absolute motion of radially directed winds at the surface of a rotating system. (Viewed from above.)

As is well known, the west—east drift of the atmosphere in middle and higher latitudes forms a gigantic polar cyclone. Now this west—east drift has its maximum at a certain level and diminishes both upward and downward therefrom. At the level of the maximum drift the centrifugal force is the greatest; below that level the air of the polar regions is drawn upward and above it the air is drawn downward; therefore, beneath this level the temperature of the air at the poles is lower than it is at the Equator, while above this level the air is warmer above the region of the poles than it is [at the same level] over the Equator. This agrees with recent observations made at great altitudes with balloons and kites at the poles and the Equator.

In Sweden certain summers, e. g., 1901 and 1914, have experienced long-continued dry weather that has been very disadvantageous to agriculture. The sun burns in a sky that is perfectly free of clouds; day and night the air temperatures are almost unbearable, rain is rare and irregularly distributed only as an accompaniment of sparsely scattered thunderstorms. Man is amazed to find that this highly heated air does not acquire a tendency to rise, for certainly it is considerably lighter than the air that overlies the countries bordering Sweden. On the contrary, some tremendous power seems to be forcing the air down upon Sweden, apparently a power far greater than the ascensional force due to the difference in specific gravity. To explain this downward force it is but necessary to assume that at some distance above [the earth] there is an anticyclonic [atmospheric] circulation around Sweden. The centrifugal force of the air is greater near the earth's surface than it is at some distance above, and therefore the air being thrown out in all directions it is strongly drawn down over Sweden. Hence the cloudless, rainless sky, the strong insolation, and the high air temperature. To explain the whole phenomenon, it is sufficient if west winds prevail in northern Scandinavia and easterly winds in southern Scandinavia. It is but a direct and simple consequence of the meteorological conditions over the North Atlantic on one side and southern Europe on the other.

We may explain the pressure distribution within cyclones and anticyclones as follows: In the cyclonic circulation of the atmosphere the centrifugal force is reinforced, and consequently barometric depressions are formed as in the familiar case of vortical movements at the surface of a body of water; on the other hand, in anticyclonic circulations centrifugal force is weakened, permitting a *consequent increase of air and of pressure*. This point of view makes many hydrographic processes also easily understood. Thus, in the horse latitudes the surface water of the Atlantic ocean is driven around in an anticyclonic circulation by the prevailing winds. Consequently, this surface water possesses a weaker centrifugal force than the bottom layers which lie in the depths of the Atlantic Basin and rotate with the rigid earth. The bottom layers of the Atlantic are, in consequence, driven laterally outward toward the rim of their basin more strongly than is the surface water. The result is that the warm surface water in the center of the anticyclonic whirl, the Sargasso Sea, is there drawn downward until it reaches even the greatest depths of the Atlantic.

In the central region of the Skagerrack one always finds the cold bottom water at a very slight depth. Although the surface water is relatively warm in summer and fall, one meets, at depths of 5 or 10 meters, with water having a temperature but a few degrees above 0°C. Along the shores of the Skagerrack, on the other hand, this cold water is not met with until considerable depths have been attained. It thus appears that there is a bulging up of the cold water in the Skagerrack. Now, it is known that the surface water of the Skagerrack has a pronounced cyclonic circulation, since there are two currents, one of which comes from the North Sea, hugging the Danish coast, the other flows from the Baltic following the southern coast of Norway. The cyclonic movement of the surface water, thus produced, signifies an intensified centrifugal force of the same whereby the water of the lower strata in the center of the Skagerrack is drawn upward.

It would be easy to multiply such examples, but I shall leave that to those readers of this essay who are interested in the methods I have described. They are easy to adopt and afford very simple explanations of a large number of meteorological and hydrographical phenomena.

DAILY MARCH OF THE METEOROLOGICAL ELEMENTS IN THE PANAMA CANAL ZONE.[1]

By Hofrat Prof. Dr. JULIUS VON HANN.

[Presented to the Imperial Academy of Sciences, Vienna, Mar. 26, 1914.]

For a number of years I have received regularly from the Chief Engineer at Culebra, Canal Zone, and at the suggestion of Prof. Cleveland Abbe, of Washington, D. C., a manuscript copy of the bihourly readings of the meteorological elements (pressure, temperature, and relative humidity) for the stations in the Canal Zone. I felt to a certain extent honor bound not to permit these valuable copies, which are sent to a very limited number of persons, to lie unused, and therefore propose to communicate the results of my computations. I have taken the mean hourly pressures for four or five years at Alhajuela, on the Rio Chagres about 10 kilometers above Gamboa, from an existing publication.[2] The stations and their geographical coordinates are given in the following table:[3]

Meteorological station.	Aspect.	North latitude.		West longitude.		Altitude. (M. S. L.)
		°	′	°	′	*Feet.*
Ancon (Panama)	Pacific coast	8	57.6	79	33	86.4
Alhajuela	Inland	9	12.3	79	37	140
Colon	Atlantic coast	9	22	79	54.5	4
Cristobal (dock)[4]	do	9	21.1	79	55.5	(?)
Culebra	Pacific inland	9	03	79	39.3	384

This table is based on data furnished October 27, 1914, in a letter from George W. Goethals, Governor of the Panama Canal. A sailing chart of the Canal[4] is now available.

The mean pressures are not corrected for gravity, but they are reduced to sea level. The barometer correction is also given for Alhajuela and was used by me in calculating the mean. The other barometer readings are probably also corrected since the yearly means agree with those for Alhajuela; but the monthly means for the latter station are not in good agreement with those for the other stations. This is probably due to the fact that the means are for other series of years (1900–1904, in part for 1899–1903; while my stations are for 1907–1912 or 1908–1913, with a few gaps). In order to better judge of the causes underlying the monthly differences in the daily march of the meteorological elements, it will be well to consider first the monthly means of the meteorological elements before discussing their daily march. The conditions of wind and rain are particularly important.

MONTHLY MARCH OF THE ELEMENTS.

The highest mean temperature and maximum atmospheric dryness occur in March and April; the lowest temperature occurs in November.

From May to December, inclusive, the atmospheric humidity is uniformly high. January to April, inclusive, are dry. Colon on the Atlantic coast is considerably the moister.

Rainfall increases from the Pacific litoral to the Atlantic coast (Ancon has 181 centimeters, Colon 318 centimeters). From January to March, inclusive, it is very dry; during these three months Ancon receives but 3.7 per cent, Culebra but 3.3 per cent, and Colon 5.5 per cent of the respective annual rainfalls. April is the transition period to the rainy season, with 4 per cent, 3.4 per cent, and 3.2 per cent, respectively. On the Pacific slope the principal rainy months are May and October and November. On the Atlantic coast at Colon the rainiest months are July and October. In the case of Alhajuela I have also computed the average rainfall and the number of rain days for the period to which the daily pressure march corresponds.

[1] The present important paper is a translation of the following:
Hann, J. v. Der tägliche Gang der meteorologischen Elemente am Panamakanal. (Vorgelegt in der Sitzung am 26. März 1914.) *Aus den* Sitzungsb. d. Kaiserl. Akad. d. Wissens. in Wien, Math.-naturw. Kl., Jänner 1914, **123**: 171–204. Wien. 1914. 34 p. 8°.

[2] Abbot, H. L. Hourly climatic records on the Isthmus of Panama. MONTHLY WEATHER REVIEW, Washington, June, 1904, **32**: 267–272.

[3] Prof. Hann adopted the following coordinates and altitudes for his work:
Ancon, latitude, 8° 57′ north; longitude, 79° 31′ west; altitude, 28 meters.
Culebra, latitude, 9° 02′ north; longitude, 79° 40′ north; altitude, 123 meters.
Alhajuela, latitude, 9° 12′ north; longitude, 79° 37 west; altitude, 44 meters.
Colon or Cristobal, latitude 9° 22′ north; longitude, 79° 55′ west; altitude, 10 meters.

But he states explicitly that these are only approximate, since they were not given in the publications available to him, and he had to estimate them from a very small sketch map in the Proceedings of the American Society of Civil Engineers, New York, January, 1913, **39**, no. 1. There is no serious discrepancy between the two sets of figures.

Culebra meteorological station was discontinued September 12, 1914.

Ancon station was moved to the near-by Balboa Heights, altitude of barometer cistern 118 feet, October 1, 1914.—[C. A., jr.]

[4] Isthmian Canal Commission. "Chart of the Panama Canal, 1904–1914. . . . Scale 1:40,000. Latitudes and longitudes are based on the Panama-Colon datum adopted in 1911. [U. S. Hydrographic Office.]" This chart is issued in two sheets, and is intended to serve for the navigation only of the canal; it gives no reliable topographic information beyond general outlines and does not extend to Alhajuela.—[C. A., jr.]